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Research article

The dominating influence of efficacy above management strategy in the long-term success of alien plant clearing programmes

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ABSTRACT

Conservation managers are required to make decisions in complex and uncertain contexts. To strengthen the robustness of conservation decisions, several approaches have been proposed to facilitate stakeholder engagement in the setting of conservation objectives and priority actions. While such processes have led to the formulation of several invasive alien plant management strategies to achieve specific objectives, the long-term consequences and trade-offs inherent in these strategies have not been tested. The performance of five of these strategies over 50 years was tested in the protected area context using empirical data from Table Mountain National Park, South Africa. A simulation model based on data for invasive *Acacia* species in a fire-driven ecosystem, focused on the interaction between strategy performance and clearing efficacy in achieving a management goal or reducing *Acacia* density to below 1 plant per hectare. At near perfect levels of clearing efficacy, all strategies converged towards reaching the management goal, while at lower efficacy levels the strategies diverged in their ability to achieve desired outcomes. Despite working across the largest area, strategies that focussed on clearing low density invasions, maintained the least area in a maintenance state over time. In contrast, strategies that focussed on a mix of post-fire, low density areas and high altitude areas cleared less area annually, but maintained a much larger area in a maintenance state. At higher levels of efficacy, strategies that return to previously worked areas were more successful than a post-fire strategy. Strategies that focused solely on securing water, performed poorly in maintaining low overall density of aliens. However, the influence of efficacy was significant and substantial and a much larger difference in area reaching the management goal was achieved by varying efficacy than varying strategy. As such, improving quality of work and implementation will have a far greater effect than which areas are prioritized or how this prioritization is done. While acacias are likely to persist in the long-term, improving work quality coupled with correct strategy selection will ensure continued gains in the area under maintenance and improved return on investment over time.

1. Introduction

Conservation managers are required to make decisions and take action in complex systems (Regan et al., 2005; Game et al., 2014) that frequently require trade-offs, in the midst of limited resources and data deficiencies (Reed, 2008). Approaches proposed to improve the robustness of decision making, such as Structured Decision Making and Systematic Conservation Prioritisation (Bower et al., 2017; Schwartz et al., 2018), entail inclusive stakeholder engagement in the setting of management objectives and priority actions to determine a management strategy. In this way, multiple management actions can be prioritized and management actions determined (Regan et al., 2005). The wide range of inputs arising from the inclusion of scientific, political, social and economic stakeholder perspectives may, however, lead to the formulation of excess or conflicting management objectives (Roper et al., 2018). It is possible that convoluted problems may result in any agreeable solution being deemed better than no solution at all (Saaty, 1990; Game et al., 2013). Acceptance of suboptimal or conflicting objectives can undermine the effective use of limited available conservation funding and resources (James et al., 1999; Bruner et al., 2004;

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Emerton et al., 2006; Ferraro and Pattanayak, 2006). Therefore the assessment of the conservation outcomes of a chosen strategy is needed to determine the potential impact of conflicting objectives.

The overall management goal of alien plant control programmes is to reduce the occurrence of Invasive Alien Plants (IAPs) to densities that have no negative impact on native biodiversity. To achieve this goal, clear objectives, strategies, adaptive planning, adequate resources and funding for long-term implementation are required (Esler et al., 2010; Foxcroft and McGeoch, 2011; van Wilgen et al., 2016a). Predictive models that consider ecological drivers such as fire, invasion rate, ecological impact and factors that increase uncertainty, such as clearing efficiency, can provide estimates of expected outcomes defined by particular sets of conservation objectives and resource allocations (Le Maitre et al., 1996; Higgins et al., 2000; Krug et al., 2010; Cheney et al., 2019). Prioritisation models for IAP management that attempt to account for multiple objectives and uncertainties have been developed for a number of applications and include water catchment areas (van Wilgen et al., 2007; Forsyth et al., 2012), protected area management (Forsyth and Le Maitre, 2011; van Wilgen et al., 2016a) and maximisation of economic cost-benefit ratios (Higgins et al., 1997; de Wit et al., 2001). However, the prioritisation of areas for management intervention is sensitive to the weighting of component factors, objectives and the availability of information (Roura-Pascual et al., 2010). In addition, the impact of strategy on priority area selection is generally only tested as a static, once-off assessment without consideration of iterative and changing reality over time (Roura-Pascual et al., 2010; Forsyth et al., 2012).

Australian *Acacia* species in South Africa pose on-going management challenges, perpetuating high long-term management costs (McConnachie et al., 2012), and are particularly difficult to control despite intensive management effort. Acacias are highly invasive globally (Richardson and Rejmánek, 2011) and have been considered a model group for studying many facets of alien plant invasions (Richardson et al., 2011; van Wilgen et al., 2011). The successful establishment and long-term persistent invasion of *Acacia* species has been attributed to a number of factors, including early maturity (<2 years), prolific production of long-lived seed (up to 12,000 seeds/m^2/annum) and prolific post-fire germination (Marchante et al., 2010; Strydom et al., 2017). This has resulted in the need for strategies that address persistent invasions. Current invasive alien plant management strategies applied in the majority of South African protected areas follow the nationally funded invasive alien plant control programme, 'Working for Water' (WfW). This programme aims to restore and maintain habitat structure and function to mitigate the loss of ecosystem services, especially water production, through creating employment opportunities and facilitating skills development that contribute to poverty alleviation (van Wilgen et al., 2012a).

The long-term prospects of candidate management strategies are particularly important in protected areas designated as biodiversity refuges. Maintenance of biodiversity and ecosystem processes are best facilitated at low alien densities. Therefore, in line with the national programme, we set a long-term overarching management goal of reducing the density of alien *Acacia* species to less than 1 plant per ha (van Wilgen et al., 2020). We assess the prospects of five management strategies identified for Table Mountain National Park (Roura-Pascual et al., 2010), as well as a sixth strategy that focused work on a core biodiversity area, for achieving this goal in the long-term. Use of a detailed ecological model (Cheney et al., 2019) allowed us to assess the success or failure of particular strategies and the magnitude of trade-offs between them. The performance of each strategy was assessed over 50 years in terms of: (i) the number of hectares that realised the management goal (ii) the hectares that were sustained in a maintenance state and (iii) the number of hectares that were treated (due to the importance of this factor for the programme's reporting). In addition, we varied implementation efficacy for each of the strategies to assess the long-term outcomes and trade-offs inherent in these strategies in relation to the need for implementation precision.

2. Materials and methods

2.1. Study area and alien plant clearing programme

Table Mountain National Park (TMNP) is located on the Cape Peninsula, South Africa, and covers approximately 25,000 ha. Historical land-use and proximity to the City of Cape Town has facilitated the arrival and spread of over 200 alien plant species into the park (Spear et al., 2011). Formalised control of IAPs commenced in the late 1980s, employing semi-skilled labour, skilled private contractors and civil society volunteer groups (Macdonald et al., 1985). Current IAP management is implemented through the WfW programme, which has been operational since 1998. While the programme seeks to reduce alien plant densities to 'maintenance levels', the programme also includes employment generation as a key target, with a focus on poverty relief, as well as targets focussed on maximizing the area in which alien clearing takes place (see 2.2). Despite the long history of control, alien plants persist in the park landscape at densities that require large, long-term management budgets (Fig. 1; van Wilgen et al., 2016a).

For model simulation and analysis we considered fine-scale data from 809 Working for Water management units (spatially mapped as GIS polygons, on average 28 ha [± 76 SD] in size) that cover 91% (22,671 ha) of the park (Cheney et al., 2018), excluding only very steep inaccessible areas. Each management unit currently has, or historically had, different levels of invasion by a range of alien plant species. The dominant taxa in TMNP are woody alien species from the genera *Acacia*, *Pinus, Eucalyptus* and *Hakea*. For the purpose of this simulation model only *Acacia* species are considered as they are the most common alien plants (Cheney et al., 2018), occupying up to ten times the area and occurring at densities of up to 250 times of other genera in the park (C. Cheney, unpublished data), thus posing the greatest threat to park biodiversity (Richardson et al., 1996).

2.2. Setting a management goal for clearing

Since 1998, the park has used a multi-priority management approach, focussing on i) recently burnt areas that target young plants, ii) maintenance clearing of lightly-invaded areas, to maintain gains of past work, iii) control in areas of medium invasion, iv) removal of pockets of very dense invasions, and v) trying to ensure an 18–24 month return interval to each management unit (i.e. before coppicing/germinated plants produce new seeds). Due to germination from long-lived, persistent seedbanks and variable clearing quality, it is currently accepted that complete eradication of *Acacia* species within the model period of 50 years is unlikely (Cheney et al., 2019). Given the current prevalence of *Acacia* and resources available to conservation managers, a realistic management goal needed to be set.

The current WfW clearing programme stipulates that failing eradication of IAPs, the best possible management outcome would be to reduce the target alien species to levels that require only maintenance clearing across the entire park. Thus, for each management unit, the management goal was set for acacias to have a density of less than 1 plant per hectare, and therefore considered 'rare' in the landscape (Le Maitre and Versfeld, 1994). In addition three main measures are monitored, based on the programme's deliverables: person days utilised, hectares treated and IAP density reduction (van Wilgen et al., 2017). The WfW programme seeks to maximise the number of employment opportunities provided by allocating work in terms of person days required as a resource input (van Wilgen et al., 2012a). Using these available person day allocations, the total number of hectares that can be treated is determined with due consideration of opportunities to reduce alien plant density.

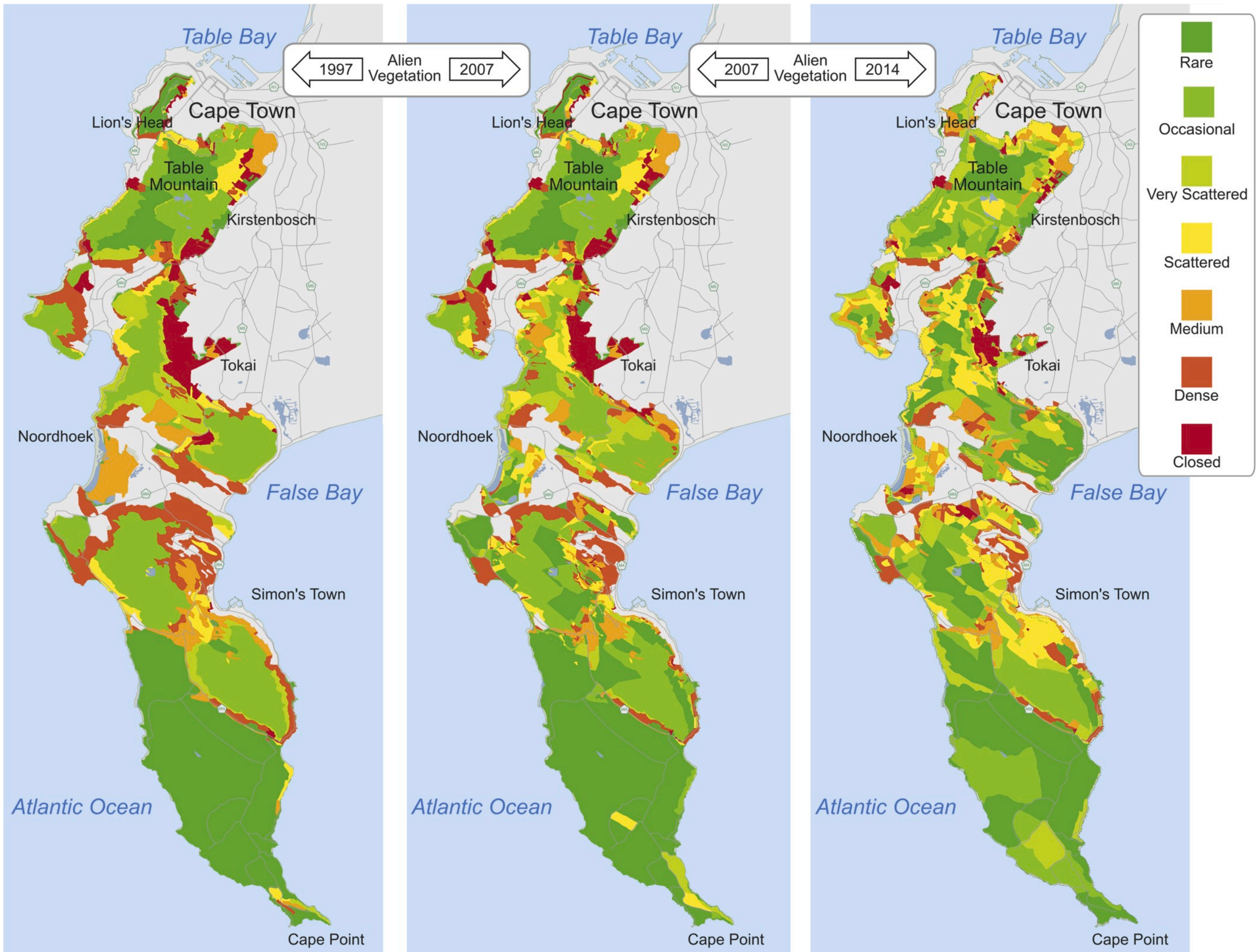


Fig. 1. The density of invasive alien plants within the Table Mountain National Park as measured by management authorities in 1997, 2007 and 2014. Source SANParks, 2016, reproduced with permission of SANParks. Changes in density over time are driven predominantly by clearing, fire and seedbank dynamics.

2.3. Simulated IAP management strategies

Four IAP management clearing strategies previously developed for TMNP through a participatory prioritisation process with managers, researchers and experts (Roura-Pascual et al., 2009, 2010) were considered for analysis. These were (renamed from the original publication where appropriate): i) Previously Treated (follow-up clearing), ii) Lightly Invaded (keep areas clean), iii) Water Production and iv) Post-fire (management consensus; see Box 1 and Sup. Table 1 for details). In addition to the four management strategies, we considered a Core-Conservation strategy (Bottrill et al., 2008), based on securing a core area of high conservation value in the park and only clearing additional areas if resources were available (Box 1). These core conservation areas were defined in terms of biodiversity value, starting from biodiversity hotspots and selecting additional areas of high conservation value as a contiguous block for exclusion of acacias.

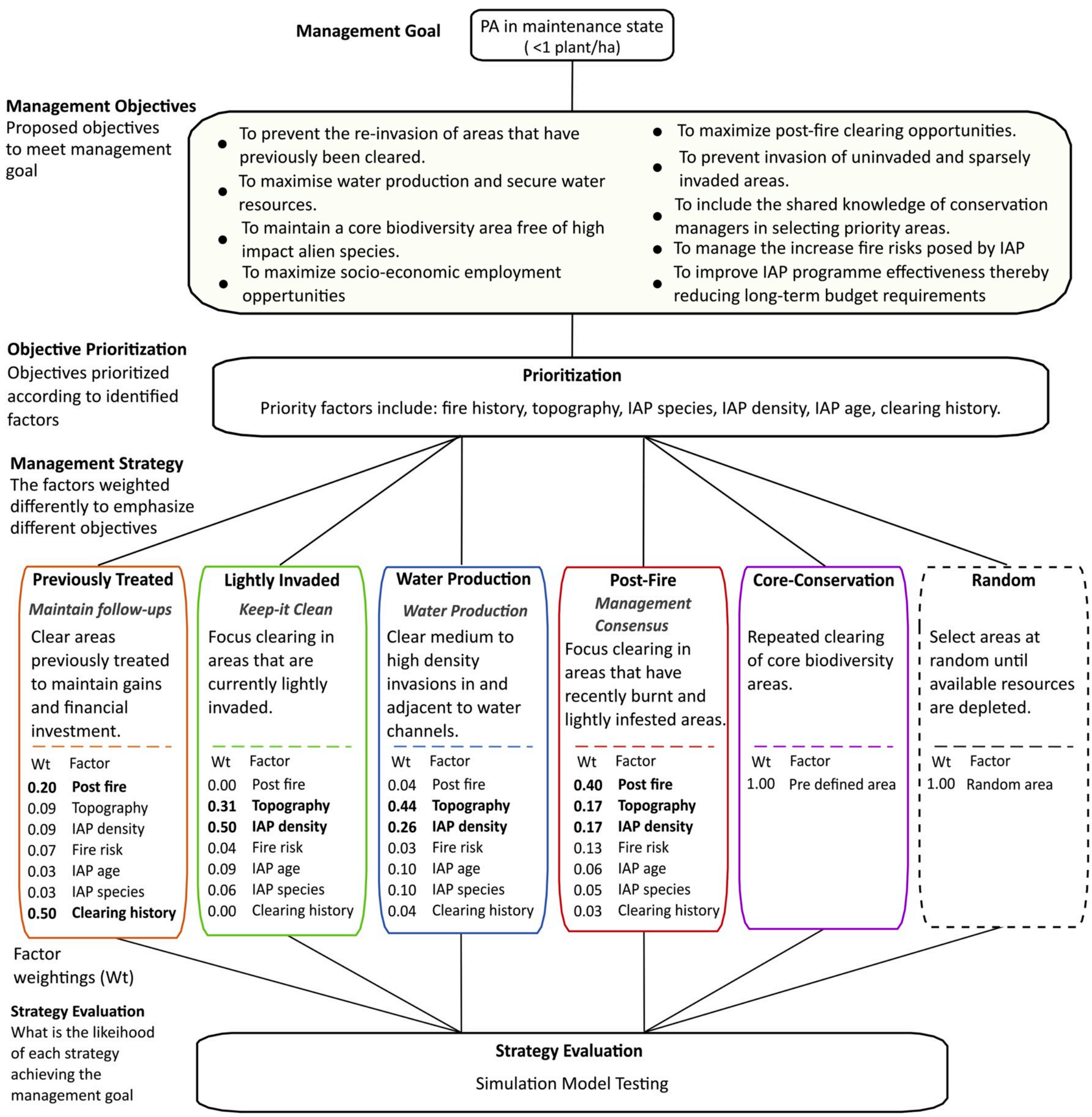
2.4. Model description

A spatio-temporal, polygon-based, population model was developed for the park using Visual Basic in MS Excel (2013 v15.0) (Supp. Fig. 1; Cheney et al., 2019). The model simulates *Acacia* population size, age structure and area invaded, within each of the 809 management units, based on two key drivers of *Acacia* persistence, namely fire dynamics and plant population (growth and seedbank) dynamics (Le Maitre et al., 1996; Higgins et al., 2000; Krug et al., 2010). Starting population data for the model (year 0) were based on fine-scale data collected from a systematic survey in-field from 10,057 plots that uniformly covered all management units (Cheney et al., 2018). The starting parameters collected in-field included three size-class differences that were carried through in the modelled environment: seedlings, six years of 'young plants' and 50 years of adult stages, with plants older than 50 years expected to have senesced. Fire dynamics were based on a park fire history dataset dating back to 1965 and has an inter fire period of 15–25 years which is typical for Mediterranean shrublands. This dataset was used in combination with vegetation age characteristics and fire intensity as determined by the Fire Danger Index, calculated based on observed daily weather recordings. Seed dynamics were based on current literature from Mediterranean regions that assessed seed accumulation rates (up to 12,000 seeds/m^2/year), annual vertical movements of seed in the soil, germination rates (up to 3% in inter-fire periods, up to 95% post-fire and post-treatment) and dispersal in the landscape (Supp. Tables 2 and 3). Full model details are provided in Cheney et al., (2019). The purpose of the current paper is to use the existing model to test the performance of each strategy in reducing invasions at different levels of clearing efficacy into the future.

The *Acacia* species included in the model were grouped based on their response to management i.e. those that i) readily coppice if not

Box 1

Translation of objectives into management strategies through weighting of environmental factors prioritized through the Analytical Hierarchy Process (Roura-Pascual et al., 2010). Refer to Supp. Table 1 for further details of each of the parameters used per strategy.



treated correctly (e.g. through the incorrect clearing method or application of herbicides), such as *Acacia saligna*, *A. mearnsii*, *A. melanoxylon*, and ii) species that do not readily coppice, namely *A. cyclops* and *A. longifolia* (Supp. Tables 2 and 3 shows how model parameters differed between these groups). The model was run for the equivalent of 50 simulation years for each management strategy. Within a model simulation year, the model time interval was set to quarterly calendar increments, aligned with current IAP clearing operations as determined by the priorities set for a particular strategy. Available resources were divided per quarter until the total available resource allocation for the year was reached. The standard resource unit for alien plant control in the park is based on the number of person days required to treat an invaded area. The park's 2017 allocation of 40,128 person days was used as the available resource with which to undertake clearing each year. Any unused person days in a simulation year were not carried over to the next simulation year.

At the start of each year, the model assessed the value of each factor and sub-factor relevant to each strategy within management units. Management units were prioritized for clearing based on scores for the factors and sub-factors used per strategy (Box 1). The scoring was done at the beginning of each simulation year so as to enable the effects of the model variables, such as fire, clearing success, seed germination, to be 'fed-back' into the model and inform the current year's prioritisation. For the Core-conservation strategy, factor weights were ignored and the management units were pre-scored based on biodiversity and conservation value and repetitive selection of the same ordered management units occurred. This directed management resources primarily into the high value conservation areas with secondary areas being treated as resources became available. For purposes of comparison, a Random strategy was introduced as a null strategy where management units were selected at random at the beginning of each model year until allocated person days had been depleted, with factor weights ignored.

Due to the variable nature of some of the model values (e.g. fire), the management strategies (see 2.5) were run for 15 iterations of each strategy at 20 incremental levels of clearing efficacy from 5 to 100% for 50 years (reported here at four levels, see 2.5). Control efficacy was taken as the collective probability that each plant present would be treated correctly (i.e. located, killed and prevented from resprouting by application of the correct treatment methodology). Efficacy within the model was allowed to vary by 5% around the mean level, thus for a model with 90% efficacy, each plant had a 90 ± 2.5% chance of being treated correctly.

2.5. Management strategy comparison

2.5.1. Basic comparison metrics

Several studies have identified a number of areas where programme efficacy could be improved (McConnachie et al., 2012; van Wilgen and Wannenburgh, 2016; Kraaij et al., 2017), without necessarily requiring an increased budget, for example by timely application of herbicide as opposed to delayed application. While these factors are not the focus of this study, given the key mediating effect of efficacy on programme success (Cheney et al., 2019), we were particularly interested in the impact of clearing efficacy on each strategy. At the start of the model (year 0), infield sampling records showed 5,646 ha (25%) were in a maintenance state, *i.e. Acacia* densoity <1 plant per hectare. The long-term outcome of the six strategies (five management and one random), was compared in terms of (i) the number of hectares that realised the set management goal of less than 1 plant per hectare, (ii) the hectares that were sustained in a maintenance state and (iii) the number of hectares that were treated, at different levels of implementation success. Metric one evaluates the ability of each strategy to improve these percentages over time. Evaluating which of these areas were sustained in a maintenance state for the duration of the model, as well as at the end of the model period, enabled assessment of the potential shift away from areas currently under maintenance to new maintenance areas under different strategies. The final metric of annual area treated forms an important component of national programme reporting. We also evaluated the number of person days (proportion of the total possible allocation) required for each strategy as a direct proxy for the amount of resource effort (model input).

We determined the value of the above metrics annually, at the model endpoint (year 50) as well as averaged over the duration of the model between years 10–50, at each of 20 efficacy levels (ranging between 5 and 100% effective). The first nine years were excluded from the analysis to allow the models to stabilize and reduce the influence of the starting parameters (especially initial plant population size) on model performance. To simplify reporting, we focus on the effect of high (0.9), medium (0.75), low (0.5) and very low (0.25) levels of implementation efficacy for model results relating to hectares at the end of year 50, with details of additional efficacy levels supplied as Supplementary Material. Differences in the outcome of each strategy (hectares cleared, reaching maintenance and sustained in a maintenance state) were compared pairwise using the Wilcox non-parametric test. To reduce the number of comparisons for reporting, we focus on comparisons of each strategy to the random model. Data analyses were conducted in R (R Development Core Team, 2013), with plots drawn using ggplot2 (Wickham, 2016).

2.5.2. Strategies frequency histograms

Each strategy was expected to select different management units for clearing at a specified level of efficacy. Over time, some management units may be selected more frequently under one strategy, but less frequently or not at all under others. Under each strategy, each management unit had 50 opportunities to be selected (one per year). Given 15 iterations per year over 50 years, each management unit could be selected a maximum of 750 times (i.e. 50 years x 15 iterations) across model runs. For each of the 809 management units, the total number of treatments received out of the possible 750 was calculated per strategy at a given efficacy level and plotted as a kernel density histogram (Wickham, 2016). In addition, a kernel density histogram based on the actual number of times each management unit was treated in the history of the clearing programme (20 years of actual treatments between 1998 and 2017), was plotted using the park's IAP clearing database (Working for Water, 2017). A normal distribution would be expected under a random strategy, whereas a uniform distribution of treatments would indicate a biased prioritisation where specific areas are constantly selected and others are consistently not selected, while remaining areas receive an increasing occurrence of clearing work. A left-skewed distribution would indicate that the majority of management units received very few or no treatments, while a right skewed distribution would indicate most management units receiving a high number of treatments. For example, the Water Production strategy is expected to produce a skewed distribution based on repeat selection of management units important for water production. Differences in the mean of the frequency distribution were tested with a Wilcox test at different levels of efficacy. Similarly kernel density histograms were plotted for the number of times each management unit achieved the goal of having *Acacia* densities below 1 plant per hectare under different efficacies. This enabled us to distinguish the proportion of areas that were being maintained as opposed to those being treated under different strategies and at different efficacies.

3. Results

3.1. Achieving the management goal

The management goal set was to achieve an *Acacia* density of lower than 1 plant/ha in a given management unit, with the area thus being considered in a maintenance state. The park had 5,646 ha (25%) and 161 (20%) management units in a maintenance state at the start of the model (i.e. year 0). All management strategies achieved a minimum average of 8400 ha (37%) and 100 (12%) management units in a maintenance state from year 10 onwards (Fig. 2) and performed significantly better than the Random strategy by year 50 at average efficacy levels ($p < 0.05$, Supp. Table 4). The strategy that achieved the highest success varied over time and at different efficacy levels (Fig. 2). Although the Lightly Invaded strategy treated the most hectares (section 3.3), this management strategy achieved the lowest number of hectares per year in a maintenance state by year 50 across all efficacy levels (36% ha ±41%SD, Fig. 2), compared to the Previously Treated strategy which achieved the most (47%ha ±32%SD; $p < 0.001$, Supp. Table 4).

Reducing clearing efficacy resulted in a sharp decline in the annual achievement of the management goal (Fig. 2a). For example, by year 50, the Post-fire strategy was able to maintain a mean of 76% of ha (±9%SD) at 0.9, compared to 58%ha (±10%SD) at 0.75, and 45% of ha (±16%SD) at 0.50 clearing efficacy level (Fig. 2, Supp. Tables 5 and 6). The Lightly Invaded and Water Production strategies only outperformed the Random strategy at very low (0.25) clearing efficacy levels (Fig. 2b, Supp. Tables 5 and 6). At high efficacy (90%), the Previously Treated strategy was the only strategy able to outperform the Random strategy at year 50, maintaining 80% of ha (±5%SD, $p < 0.05$, Fig. 2b, Supp. Table 6). However, at 75% clearing efficacy, the Post-fire and Conservation-core strategies maintained significantly more hectares (±58%ha, Fig. 2b, Supp. Table 6) than the Random or Previously Treated strategy. While there were not large differences in the long-term outcome between several of the strategies, some strategies do consistently better than others at maintaining large areas (Fig. 2b), but importantly, efficacy has a much greater impact on the area maintained over time than strategy does (Fig. 2).

3.2. Maintenance areas sustained

At 100% clearing efficacy, all areas currently in a maintenance state (25% of ha) remained in this state under all management strategies.

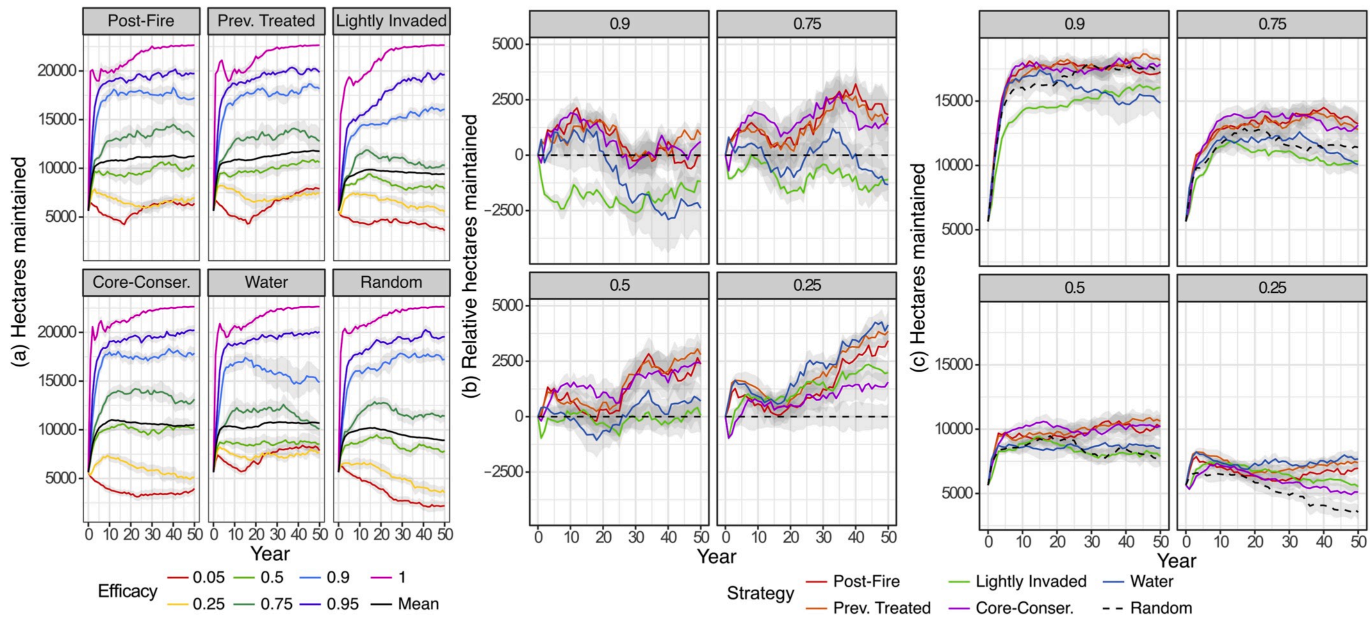


Fig. 2. Effect of clearing efficacy on (a) the number of hectares that reached a maintenance state of 1 plant per ha over 50 years for each of the management strategies and relative performance of the strategies in the number of hectares that reached a maintenance state over 50 years (b) in comparison to the random strategy and (c) one another at four management efficacy levels (0.25, 0.50, 0.75 and 0.90), represented by the mean and 95% CI of 15 model runs per efficacy level. Supp. Fig. 2a shows all 20 levels of efficacy tested; and results of comparisons between strategies are presented in Supp. Tables 4-6.

When clearing efficacy decreased below this level, there was a shift away from the current areas under maintenance to new areas, for all management strategies. Overall, management strategies retained half the area and a quarter of the management units that were initially in a maintenance state in a continued maintenance state across all levels of clearing efficacy by year 50 (Supp. Fig. 4; Supp. Table 7). All but the Lightly Invaded strategy sustained significantly more hectares in a continued maintenance state than the Random strategy (Supp. Fig. 4; Supp. Table 7). As clearing efficacy levels decreased, there was a steady decline in continued maintenance of areas at the start of the model under all management strategies (Supp. Fig. 4; Supp. Tables 8 and 9). Only at 25% clearing efficacy levels did all the management strategies perform better than the Random strategy (Supp. Fig. 4b; Supp. Table 9) in retaining hectares in a maintenance state.

3.3. Area treated

At 100% efficacy all management strategies were able to clear all hectares from early on in the model simulation, indicating that the choice of prioritisation strategy becomes irrelevant when all plants in a target area are treated and killed. As with other indicators, however, clearing efficacy had a significant effect on the mean hectares and

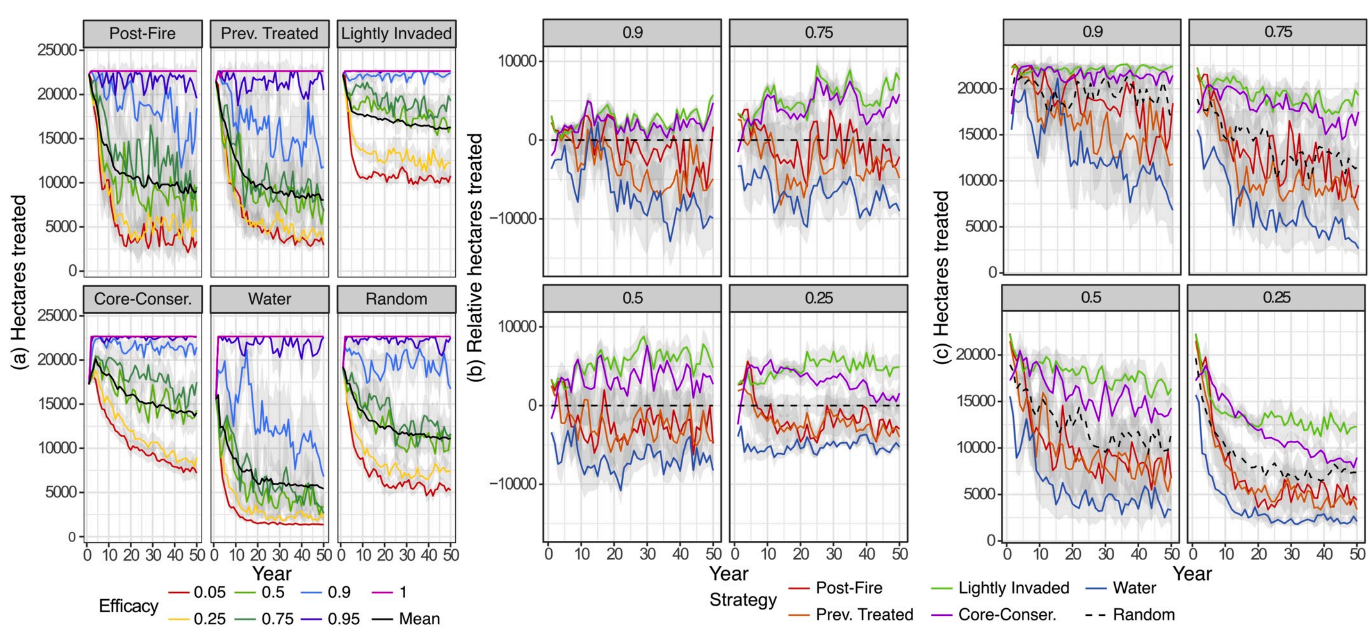


Fig. 3. Effect of clearing efficacy on (a) the number of hectares treated per year over 50 years for each management strategy and relative strategy performance in the number of hectares treated per year over 50 years (b) in comparison to the random strategy and (c) on another at four management efficacy levels (0.25, 0.50, 0.75 and 0.90), represented by the mean and 95% CI of 15 model runs per efficacy level. Supp. Fig. 2c shows all 20 tested levels of efficacy.

management units that could be treated, for all strategies (Fig. 3a, Supp. Table 10, 11). As efficacy declines, the area that can be treated declines over time (Fig. 3) which translates directly into the area that can be maintained by year 50 (Fig. 4). At all efficacy levels, there are significant differences in the area treated by each strategy and these differences increase at higher efficacy (Fig. 4). However, for a given efficacy, the strategy followed mediates how much area can be maintained relative to area treated. For example, while the Lightly Invaded and Conservation-core strategies consistently treat the largest area ($p < 0.001$, other strategies treated less area than the Random strategy, Figs. 3b and 4, Supp. Table 10), the Lightly Invaded strategy maintains less area than most other strategies (Fig. 4). Despite treating less than half the area (Fig. 3c, 4), Post-fire and Previously Treated strategies performed significantly better at maintaining area compared to Lightly Invaded (Figs. 2c and 4).

3.4. Summary of model performance across metrics

Although there is variation in the performance of management strategies, there are a few consistent trends. Firstly, the Previously Treated strategy performed best in relation to achieving the management goal of reducing areas to a maintenance state (Table 1; Fig. 4), while the Lightly Invaded and Water strategies largely performed the worst in this regard, despite that Lightly Invaded treated the most hectares (Table 1). The Post-fire, Conservation-core and Previously Treated strategies performed consistently well (over various efficacy levels) in sustaining areas that are currently clear in a maintenance state, while the Lightly Invaded and Water Production strategies saw larger moves away from areas that currently have low levels of invasion. The Water Production strategy was generally the worst performer across indicators while the Post-fire, Previously Treated and Conservation-core strategies consistently fared well across most indicators. At moderate to high efficacy, the Core-conservation strategy fares particularly well at maximizing both area maintained, as well as area treated (Fig. 4).

3.5. Resource effort used

The number of person days required by all management strategies was similar (Fig. 5). At 100% efficacy the number of required person days declined to below 10,000 from year 20 onwards (Fig. 5a), thereby not using the full available annual budget. As clearing efficacy decreased (i.e. a lower percentage of plants were removed successfully), the number of person days utilised annually remained high and near the maximum possible allocation. The Post-fire and Previously Treated strategies required around 38,000 person days (95% of allocation) for clearing efficacy levels between 0.75 and 0.90. For the Water Production and Lightly Invaded strategies, all person days were utilised in all years where clearing efficacy levels dropped below 0.9 (Fig. 5a). The impact of efficacy had a much greater effect on cumulative costs than the particular strategy selected (Fig. 5b). For example, the cumulative mean person days used after 50 years at 0.95 efficacy for all strategies was 1.4 million person days, compared to 2.0 million person days at efficacy levels of 0.50. This difference amounts to the equivalent person days of 15 years of clearing, which in existing (2019) project budgets amounts to ZAR300 million.

3.6. Treatment frequency distribution under different strategies

Treatment frequency per management unit (i.e. the number of times a particular management unit is selected for treatment over the full

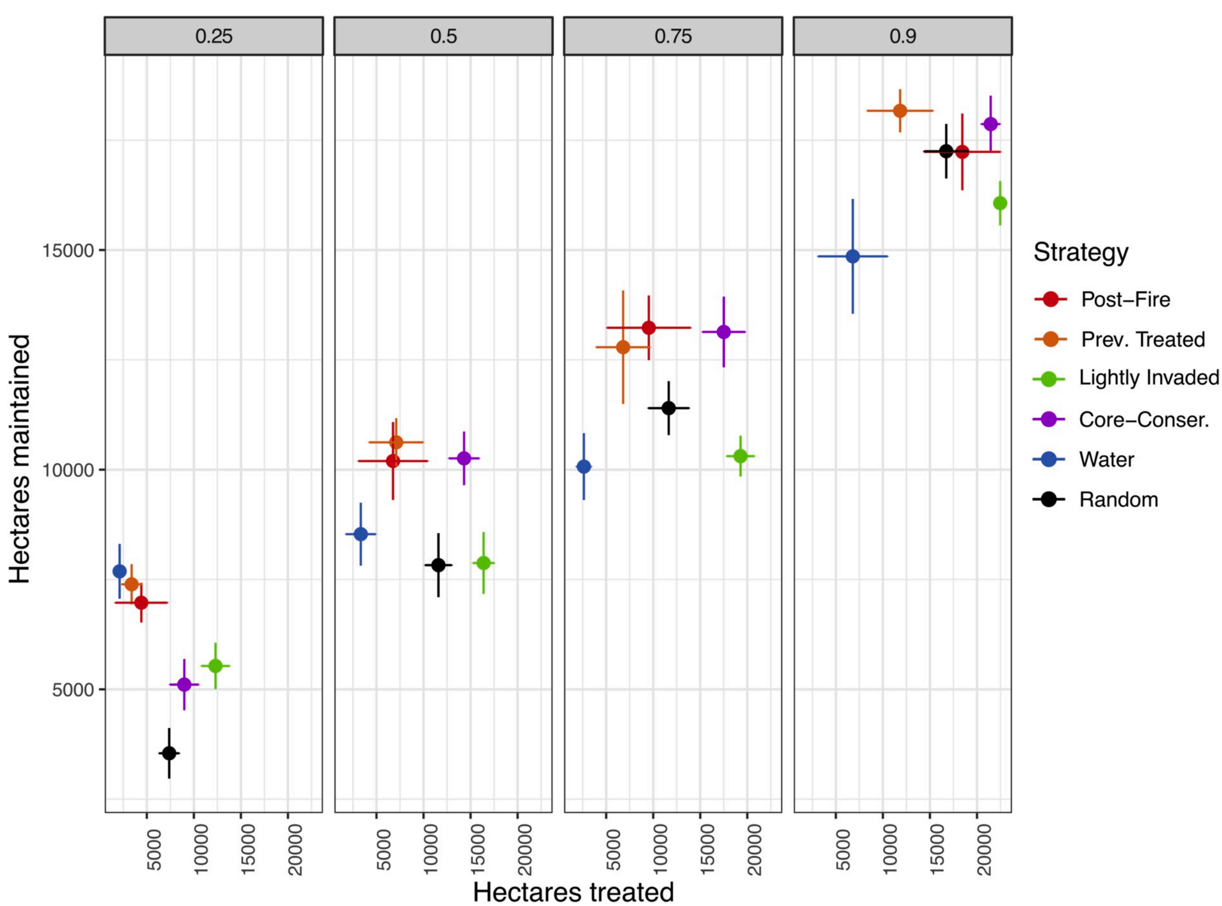


Fig. 4. The relationship between hectares treated (cleared) and hectares maintained in year 50 under six management strategies at four efficacy levels (0.25, 0.50, 0.75 and 0.90). Each dot represents the mean outcome for a strategy in year 50 and the bars represent the 95% CI based on the 15 model simulations.

Table 1
Management strategies that performed best and worst in terms of hectare-based outcomes. The random strategy is not considered as a contender for best or worst strategy. Unless otherwise stated, all 'Best' strategies perform significantly better than random, while 'Worst' strategies performed worse than random (as tested with a Wilcox test, Supp Table 13). Detailed comparisons, including comparisons averaged over time and at the model endpoint, as well as comparisons between individual strategies are presented in Supp. Tables 2 to 10 as indicated in [square brackets].

		Clearing efficacy averaged over 0.05-0.9	0.95 Clearing efficacy	0.9 Clearing efficacy	0.75 Clearing efficacy	0.5 Clearing efficacy	0.25 Clearing efficacy
Hectares **Maintained** at year 50 [Supp. Table 4-6]	**Best**	All strategies perform better than random Previously Treated significantly better than others	All strategies equal	Previously Treated	Post-Fire Core Conservation	Previously Treated Post-Fire Core Conservation	All strategies perform better than random Water Production Previously Treated Post-Fire significantly better than others
Hectares **Sustained** at year 50 [Supp. Table 7-9]	**Best**	Previously Treated Post-Fire Core Conservation Water Production	All strategies equal	All strategies but Water Production performed equal to random	Post-Fire Core Conservation	Post-Fire Previously Treated Core Conservation	Previously Treated Water Production Post-Fire Core Conservation
Hectares **Treated** at year 50 [Supp. Table 10-12]	**Best**	Lightly Invaded Core Conservation	All strategies equal	Lightly Invaded Core Conservation	Lightly Invaded Core Conservation	Lightly Invaded Core Conservation	Lightly Invaded
Hectares **Maintained** at year 50 [Supp. Table 4-6]	**Worst**	Lightly Invaded performed worst, but still better than random	All strategies equal	Water Production	Lightly Invaded Water Production	Lightly Invaded Water Production performed equal to random	Lightly Invaded Core Conservation performed worst, but still better than random
Hectares **Sustained** at year 50 [Supp. Table 7-9]	**Worst**	Lightly Invaded performed equal to random	All strategies equal	Water Production	Lightly Invaded	Lightly Invaded Water Production performed equal to random	Lightly Invaded performed equal to random
Hectares **Treated** at year 50 [Supp. Table 10-12]	**Worst**	Water Production	All strategies equal	Water Production	Water Production	Water Production Previously Treated	Water Production Previously Treated Post-Fire

model implementation) declined for all strategies with a reduction in clearing efficacy, as indicated by a left-shift in peak kernel density of treatment frequency (Fig. 6 in comparison to Supp. Fig. 5). In other words, a smaller number of management units were repeatedly selected over the model period at lower clearing efficacy. For example, the Post-fire strategy had its highest kernel density at a treatment frequency of 0.7 when clearing efficacy was 0.75, whereas the peak frequency decreased to 0.35 at clearing efficacies of 0.25. Historical clearing implementation has its peak treatment frequency at roughly 0.45 which was a significantly lower repeat frequency ($p < 0.001$) than that achieved by all the models except the Water Production model (p = NS). At 50% clearing efficacy levels, the Post-fire, Previously Treated and Lightly Invaded strategies still maintained the peak cluster densities at a treatment frequency of >0.50. This treatment frequency was significantly ($p < 0.01$) better than the current observed park treatment frequency of 0.45. However, the return on area investment for the Lightly Invaded strategy was low, as evidenced by the large separation in density peaks for maintenance versus treatment (Fig. 6). Even a high treatment frequency of a large proportion of areas produced minimal results in terms of ensuring that most areas are maintained and stay in a maintenance state over time (Fig. 6). In contrast, the Conservation-core, Previously Treated and Post-fire strategies had peak kernel densities of

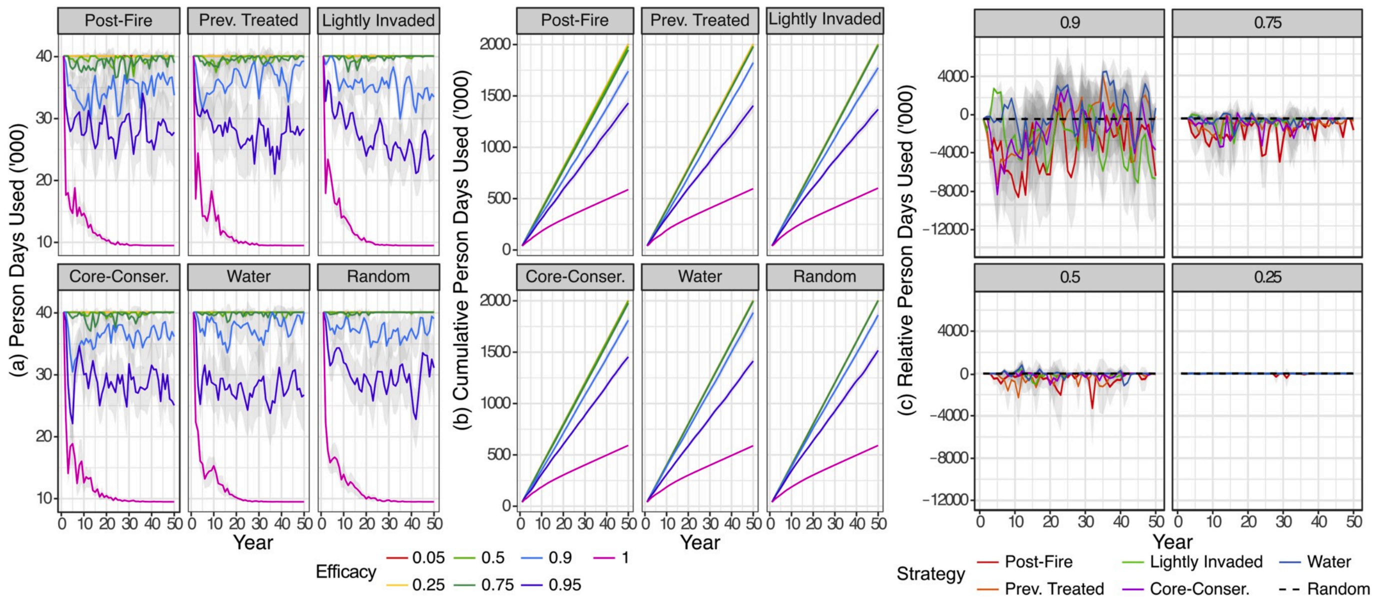


Fig. 5. The number of person days used annually (a) and the cumulative person days used over 50 years (b) for each of the management strategies at given levels of efficacy, represented by the mean and 95% CI of 15 model runs per efficacy level. Panel (c) shows the mean number of person days used under each strategy annually in comparison to a random assignment of person days, with 95% CI over 15 model runs, at each of four efficacy levels.

management units reaching maintenance above 0.3, which implies that the majority of areas reached a maintenance state for a third of the modelled period (Fig. 6).

4. Discussion

The long-term performance of five IAP management strategies was tested over a 50 year simulation of *Acacia* dynamics in Table Mountain National Park. The simulation was based on factors that are broadly applicable to *Acacia* invasions in mediterranean fire-driven systems. We assessed the interaction between strategy performance and clearing efficacy in reducing *Acacia* densities to maintenance levels. While the choice of prioritisation strategy had significant implications when implementation was imperfect, the influence of efficacy on the area achieving the goal was substantial and significantly larger than achieved by varying strategy. For example, the model analysis showed that as implementation quality declined, certain strategy-based selections performed worse than random area selection. Given that *Acacia* invasions are driven by fire and seedbanks (Richardson et al., 2011; van Wilgen et al., 2011), if a strategy does not track germination dynamics (e.g. by targeting post-fire environments), a random strategy may fare equally well. The models also showed that treating large areas did not necessarily translate into the achievement of low *Acacia* density across the park. That is, focussing on sites of already low alien density (Lightly Invaded strategy) resulted in fewer hectares in a maintenance state than for other strategies. At efficacy levels approximating those of current WfW programme implementation, the Post-fire strategy achieved the highest number of hectares and retention of current hectares in a maintenance state. While this finding suggests that the Post-fire strategy is the most appropriate for clearing efficacy levels currently observed in the park, the models also indicate that a Previously Treated strategy becomes more appropriate at higher implementation efficacy.

Despite IAP strategies based on achieving multiple objectives, having been in place for more than 30 years in the study area (Macdonald et al., 1985), a formal assessment of potential trade-offs between strategies has not been undertaken. This paper addresses the gap by assessing the ecology of acacias in relation to efficacy and timing of management interventions. In the sections that follow, we assess these trade-offs, and unpack some of the limitations of the various management strategies that have been formulated to address a range of stakeholder objectives.

4.1. Not all strategies deliver the desired conservation outcome

Modelling showed that over time, strategies were divergent in the areas that were selected for clearing (Fig. 6, Supp. Fig. 5). This finding is consistent with previous work that tested management strategies for sensitivity in area selection (Roura-Pascual et al., 2010). Divergent area selection results in each strategy setting a different management trajectory which did not converge over the 50 years modelled. For example, the Water Production strategy achieved the least number of hectares in maintenance across the park. While water security may be enhanced by this strategy initially, dedication of resources by this strategy to areas that are readily reinvaded puts the programme on a trajectory that does not serve the overall conservation goal. Over time, the sustainability of the strategy is undermined as the surrounding landscape is impacted by invasion, perpetuating the need for repeat clearing in the waterways as propagules reinvade from outside (Vardien et al., 2012). While it is unlikely that Water production would be used as a primary strategy in conservation areas, this strategy is commonly promoted at larger scales (van Wilgen et al., 2007; Forsyth et al., 2012).

4.2. Not all strategies are underpinned by satisfactory objectives

While objectives may arise from genuine stakeholder concern and with legitimate rationale, the influence of seemingly benign objectives in development and implementation of strategies may, in some cases, undermine the programme. One such example is a focus on waterways to enhance water security. While this is an important objective in a water scarce country, McConnachie et al. (2012) showed that given programme inefficiencies, 695 years of clearing would be required to keep a sizable water catchment clear, providing very limited water returns, even with the unrealistic assumption of no spread from/to other areas. Another target frequently used as a metric of successful control is to maximise the area covered by the programme (Working for Water Programme, 2017). As a result, 'hectares cleared' is an important monitoring metric, maximized by the Lightly Invaded strategy. While employing this strategy did cover the greatest area over time, failure to rapidly respond to post-fire seed germination, meant that the Lightly

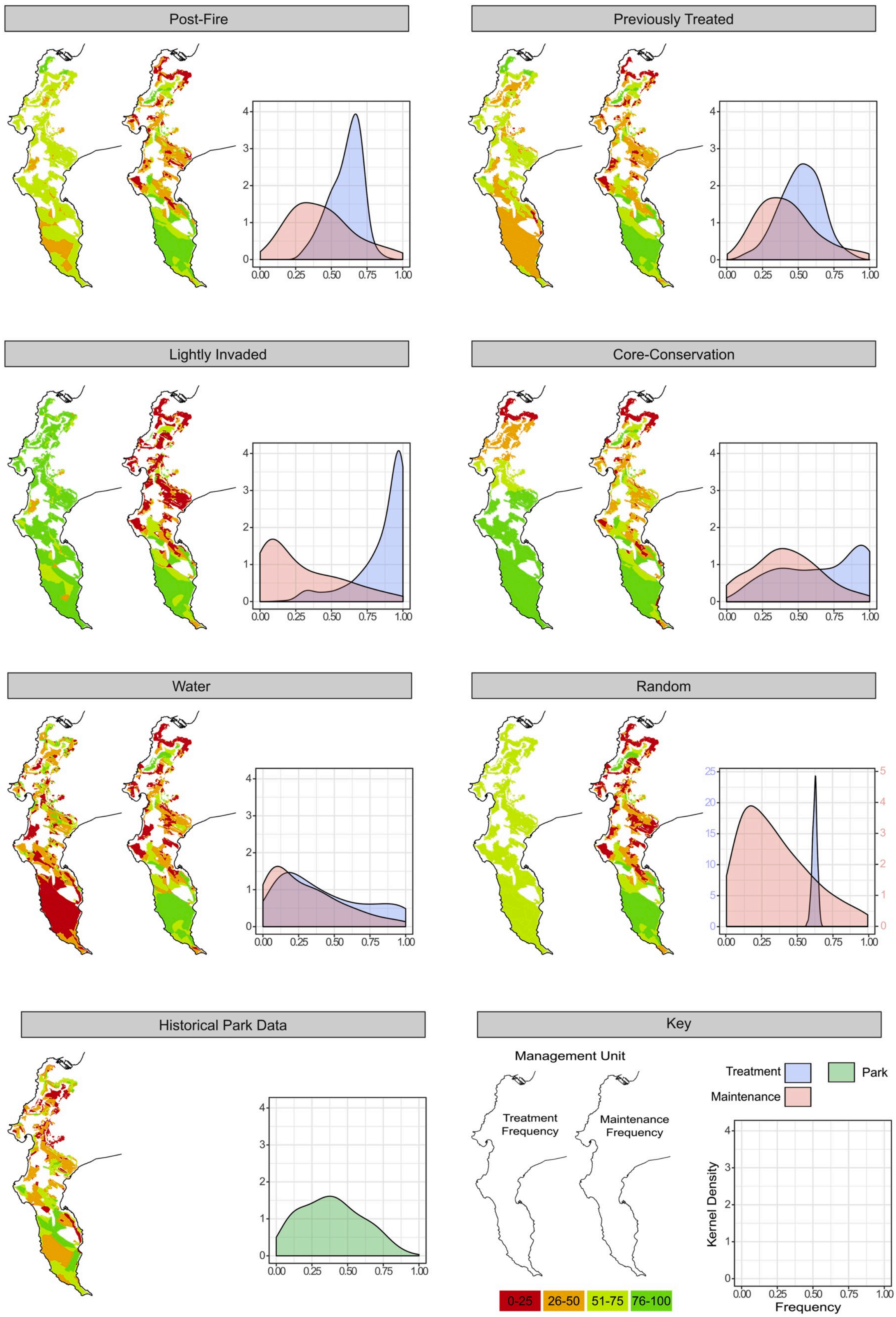


Fig. 6. Spatial representation of the frequency that management units were selected by different management strategies and the frequency that the unit achieved a maintenance state at 75% clearing efficacy, over 50 model years and 15 iterations. The actual frequency of treatments received per unit in the park between 1998 and 2017 is shown in the Historical park data block. See Supp. Fig. 5 for spatial representation of 25% clearing efficacy.

Invaded strategy performed consistently poorly in maintaining aliens at low density. Indeed, this research suggests that focussing on high biodiversity priority areas first (Core-conservation), and working until these areas are clear, is in fact a better strategy than spreading efforts across multiple low-density areas (van Wilgen et al., 2012b). The key difference between the strategies is that a Core-conservation approach would not avoid 'obstacles' (areas of high density invasion) within the core area, while a Lightly Invaded approach would avoid these denser patches.

4.3. Not all objectives are complementary and lead to divergent strategies

Accommodating divergent stakeholder views may lead to objectives that are not complementary (Reed, 2008). For example, at 75% efficacy, the Post-fire strategy achieved the highest hectares in a maintenance state while utilising the least number of person days. Although lower resource requirements may be seen as a positive, diminishing workloads is in direct conflict with the job creation objective of the Working for Water programme, which seeks to maximise employment (Koenig, 2009; van Wilgen et al., 2017). In contrast, less efficient strategies that maximise area treated and resource requirements such as the Lightly Invaded strategy would better realize the employment and area coverage objectives, while failing to achieve the desired conservation outcome. There is therefore a need to constantly engage with funders to ensure that conservation objectives are not compromised by funder-driven objectives (van Wilgen et al., 2016b). Finding a compromise is however important, and the Conservation-core strategy covers a comparably large area without compromising on the maintenance area achieved (Fig. 4). We recognise that in many situations, funders may actively seek to reduce long-term funding requirements for IAPs and strategies such as Previously Treated, and paying attention to post-fire areas in fire-driven systems, would provide the best returns in this regard.

4.4. Not all strategies are popular and so may not be adopted

In general, conservation managers can be resistant to altering or adopting new management approaches, being more comfortable with personal experience (Cook et al. 2009, 2012; McConnachie and Cowling, 2013). All simulation models show shifts away from areas currently in a maintenance state when strategies are switched, which runs contrary to managers' natural tendency to 'maintain gains' in areas that have received significant historical work (Forsyth and Le Maitre, 2011; Forsyth et al., 2012).

Focussing exclusively on high value conservation areas as a way to maintain core biodiversity areas has been proposed in the face of limited resources (Bottrill et al., 2008, 2009; van Wilgen et al., 2016a, 2016b). Although Conservation-core management has drawn both positive and negative views as a viable conservation strategy, the strategy of 'abandoning' lower priority sites sits uneasy as a plausible management approach (Jachowski and Kesler, 2009; Parr et al., 2009; Gerber, 2016). In the range of simulation models tested, the Conservation-core strategy that focused on repeatedly treating a core area and, when possible, treating additional secondary areas, performed very well. However, given that protected areas have already been prioritized to deliver biodiversity objectives and require immediate conservation action, a further prioritisation could be seen as self-defeating (Game et al., 2013). Prioritisation could be applied at a broader landscape level where a 'triage approach' is necessary (van Wilgen et al., 2020). As such, protected areas could be viewed as the core conservation area, with funding and effort predominantly directed to these sites. van Wilgen et al. (2016a) calculated that it would take 84 years to bring *Acacia* species under control in designated protected areas in the Cape Floristic Region if all funding and resources were available. Our models indicate that even this is unlikely without 100% efficacy suggesting that using limited available funding to control widespread *Acacia* invasions outside of protected areas does not appear to be a financially viable option. Extensive and collaborative planning between state and private land-owners is required to determine which areas should be kept clear of acacias.

4.5. A way forward

While an increasing number of studies have focused on the effectiveness of alien clearing programmes, only a few (e.g. Higgins et al., 2000; van Wilgen et al., 2016a) have attempted to model the future impact of alternate prioritisation strategies. These simulations of future invasions have focussed on funding scenarios, as opposed to efficacy of clearing in relation to *Acacia* ecology. The focus on funding leads to the conclusion that dramatic budget increases are required (van Wilgen et al., 2016a). We, however, argue that this need to increase budgets for successful IAP management is not a universal requirement.

Our analysis demonstrates that at a 50% efficacy level, the park would be able to maintain more area than is currently in maintenance by year 50. This level of clearing work is met within the current park area and can undoubtedly be bettered with available funding (~15% of budget is allocated to training; unpublished park data). Indeed, te Beest et al. (2017) demonstrated that with the incorporation of flexibility, adequate monitoring and quality inspections, significant efficacy improvement is possible within the current WfW clearing operations model. In many instances, improving compliance is as simple as checking that work has actually taken place (McConnachie et al., 2012; Kraaij et al., 2017).

A further constraint of previous models is that *Acacia* density was reduced at set increments with each round of clearing that ultimately led to local eradication (Higgins et al., 2000; van Wilgen et al., 2016a). The nature of *Acacia* invasions is such that even if a single adult plant is missed (99.9% efficacy), the invasion will be perpetuated, as a single adult plant can add up to 12,000 seeds per year into the seedbank (Marchante et al., 2010; Strydom et al., 2017). Therefore <100% efficacy is a global reality. Improving efficacy in places where clearing teams comprise highly skilled well-trained labour is arguably more difficult and costly. Under these circumstances improvements can be more nuanced and focus should be on factors that underpin successful strategies. These include timely return to areas previously treated, and ensuring that while lightly-infested areas are dealt with, more dense invasions between these are not neglected, such that a contiguous core conservation area is maintained.

In terms of area selection, our models show that ineffective treatment of large areas (i.e. doing a lot of work very poorly) would not achieve much progress towards the maintenance goal (e.g. the Lightly Invaded strategy below 75% efficacy). Focussing poor work in one area did however fare better over time (e.g. Core-conservation strategy). Therefore in situations where efficacy is known to be low, smaller areas can be targeted, with a focus on improved efficacy. Shifting from a strategy focus to an efficacy focus will significantly improve the achievement of conservation targets and therefore increase the long-term return on investment.

5. Conclusion

While a recent review of alien clearing effectiveness calls for effective prioritisation, van Wilgen et al. (2020) also recognise that two of the current factors inhibiting progress are monitoring of programme inputs (e.g. funds spent) as opposed to outputs and confusion over priorities as a result of having too many goals. The complex socio-ecological realities of alien management are such that the needs of multiple stakeholders will always have to be considered. However, the implementation of stakeholder-directed strategies without infield outcomes-based monitoring (Blossey, 1999; van Wilgen et al., 2012b; Fill et al., 2017), means their success remains untestable. Going forward, we advocate that core monitoring should focus on a simple measure of programme outcomes (e.g. hectares in maintenance). In addition, efficacy monitoring will be critical to distinguish the effects of poor strategy versus poor implementation. Our finding that improving quality of work will have a far greater effect than the strategy or prioritisation of particular objectives is significant for balancing stakeholder and conservation needs. With due consideration of all the potential strategies for IAP management, the focus should be on improving the efficacy of whichever strategy is selected.

Declaration of competing interest

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper, and there is no potential competing interests.

CRediT authorship contribution statement

Chad Cheney: Conceptualization, Data curation, Formal analysis, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Karen J. Esler:** Writing - original draft, Writing - review & editing, Visualization. **Llewellyn C. Foxcroft:** Writing - original draft, Writing - review & editing. **Nicola J. van Wilgen:** Formal analysis, Visualization, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110836.

References

Blossey, B., 1999. Before, during and After: the need for long-term monitoring in invasive plant species management. Biol. Invasions 1, 301–311.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A., Possingham, H.P., 2008. Is conservation triage just smart decision making? Trends Ecol. Evol. 23, 649–654.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A., Possingham, H.P., 2009. Finite conservation funds mean triage is unavoidable. Trends Ecol. Evol. 24, 183–184.

Bower, S.D., Brownscombe, J.W., Birnie-Gauvin, K., Ford, M.I., Moraga, A.D., Pusiak, R.J.P., Turenne, E.D., Zolderdo, A.J., Cooke, S.J., Bennett, J.R., 2017. Making tough choices: picking the appropriate conservation decision-making tool. Conserv. Lett. 11, e12418.

Bruner, A.G., Gullison, R.E., Balmford, A., 2004. Financial costs and shortfalls of managing and expanding protected-area systems in developing countries. Bioscience 54, 1119–1126.

Cheney, C., Esler, K.J., Foxcroft, L.C., van Wilgen, N.J., 2019. Scenarios for the management of invasive Acacia species in a protected area: implications of clearing efficacy. J. Environ. Manag. 238, 274–282.

Cheney, C., Esler, K.J., Foxcroft, L.C., van Wilgen, N.J., McGeoch, M.A., 2018. The impact of data precision on the effectiveness of alien plant control programmes: a case study from a protected area. Biol. Invasions 20, 3227–3243.

Cook, C.N., Carter, R.W., Fuller, R.A., Hockings, M., 2012. Managers consider multiple lines of evidence important for biodiversity management decisions. J. Environ. Manag. 113, 341–346.

Cook, C.N., Hockings, M., Carter, R.W., 2009. Conservation in the dark? The information used to support management decisions. Front. Ecol. Environ. 8, 181–186.

de Wit, M.P., Crookes, D.J., van Wilgen, B.W., 2001. Conflicts of interest in environmental management: estimating the costs and benefits of a tree invasion. Biol. Invasions 3, 167–178.

Emerton, L., Bishop, J., Thomas, L., 2006. Sustainable Financing of Protected Areas: A Global Review of Challenges and Options. IUCN.

Esler, K.J., van Wilgen, B.W., te Roller, K., Wood, A., Merwe, J., 2010. A landscape-scale assessment of the long-term integrated control of an invasive shrub in South Africa. Biol. Invasions 12, 211–218.

Ferraro, P.J., Pattanayak, S.K., 2006. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. PLoS Biol. 4, e105.

Fill, J.M., Forsyth, G.G., Kritzinger-Klopper, S., Le Maitre, D.C., van Wilgen, B.W., 2017. An assessment of the effectiveness of a long-term ecosystem restoration project in a fynbos shrubland catchment in South Africa. J. Environ. Manag. 185, 1–10.

Forsyth, G.G., Le Maitre, D.C., 2011. Prioritising national parks for the management of invasive alien plants: report on the development of models to prioritise invasive alien plant control operations. In: CSIR Natural Resources and the Environment Report Number: CSIR/NRE/ECO/ER/2011/0036/B. CSIR, Stellenbosch.

Forsyth, G.G., Le Maitre, D.C., O'Farrell, P.J., van Wilgen, B.W., 2012. The prioritisation of invasive alien plant control projects using a multi-criteria decision model informed by stakeholder input and spatial data. J. Environ. Manag. 103, 51–57.

Foxcroft, L.C., McGeoch, M., 2011. Implementing invasive species management in an adaptive management framework. Koedoe 53 (2), 11. https://doi.org/10.4102/koedoe.v53i2.1006. Art. #1006.

Game, E.T., Kareiva, P., Possingham, H.P., 2013. Six common mistakes in conservation priority setting. Conserv. Biol. 27, 480–485.

Game, E.T., Meijaard, E., Sheil, D., McDonald-Madden, E., 2014. Conservation in a wicked complex world; challenges and solutions. Conserv. Lett. 7, 271–277.

Gerber, L.R., 2016. Conservation triage or injurious neglect in endangered species recovery. Proc. Natl. Acad. Sci. 113, 3563–3566.

Higgins, S.I., Azorin, E.J., Cowling, R.M., Morris, M.J., 1997. A dynamic ecological-economic model as a tool for conflict resolution in an invasive-alien-plant, biological control and native-plant scenario. Ecol. Econ. 22, 141–154.

Higgins, S.I., Richardson, D.M., Cowling, R.M., 2000. Using a dynamic landscape model for planning the management of alien plant invasions. Ecol. Appl. 10 (6), 1833–1848.

Jachowski, D.S., Kesler, D.C., 2009. Allowing extinction: should we let species go? Trends Ecol. Evol. 24, 180.

James, A.N., Gaston, K.J., Balmford, A., 1999. Balancing the Earth's accounts. Nature 401, 323.

Koenig, R., 2009. Unleashing an army to repair alien-ravaged ecosystems. Science 325, 562–563.

Kraaij, T., Baard, J.A., Rikhotso, D.R., Cole, N.S., van Wilgen, B.W., 2017. Assessing the effectiveness of invasive alien plant management in a large fynbos protected area. Bothalia 47, 1–11.

Krug, R., Roura-Pascual, N., Richardson, D.M., 2010. Clearing of invasive alien plants under different budget scenarios: using a simulation model to test efficiency. Biol. Invasions 12, 4099–4112.

Le Maitre, D.C., Van Wilgen, B.W., Chapman, R., McKelly, D., 1996. Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. J. Appl. Ecol. 161–172.

Le Maitre, D.C., Versfeld, D.B., 1994. Field Manual for Mapping Populations of Invasive Plants for Use with the Catchment Management System. Department of Environment Affairs, Pretoria, South Africa.

Macdonald, I.A.W., Jarman, L., Beeston, P., 1985. Management of Invasive Alien Plants in the Fynbos Biome. Foundation for Research Development, Council for Scientific and Industrial Research.

Marchante, H., Freitas, H., Hoffmann, J.H., 2010. Seed ecology of an invasive alien species, *Acacia longifolia* (Fabaceae), in Portuguese dune ecosystems. Am. J. Bot. 97, 1780–1790.

McConnachie, M.M., Cowling, R.M., 2013. On the accuracy of conservation managers' beliefs and if they learn from evidence-based knowledge: a preliminary investigation. J. Environ. Manag. 128, 7–14.

McConnachie, M.M., Cowling, R.M., van Wilgen, B.W., McConnachie, D.A., 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. Biol. Conserv. 155, 128–135.

Parr, M.J., Bennun, L., Boucher, T., Brooks, T., Chutas, C.A., Dinerstein, E., Drummond, G.M., Eken, G., Fenwick, G., Foster, M., Martínez-Gómez, J.E., Mittermeier, R., Molur, S., 2009. Why we should aim for zero extinction. Trends Ecol. Evol. 24, 181.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. Vienna, Austria.

Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431.

Regan, H.M., Ben-Haim, Y., Langford, B., Wilson, W.G., Lundberg, P., Andelman, S.J., Burgman, M.A., 2005. Robust decision-making under severe uncertainty for conservation management. Ecol. Appl. 15, 1471–1477.

Richardson, D.M., Carruthers, J., Hui, C., Impson, F.A.C., Miller, J.T., Robertson, M.P., Rouget, M., Le Roux, J.J., Wilson, J.R.U., 2011. Human-mediated introductions of Australian acacias – a global experiment in biogeography. Divers. Distrib. 17, 771–787.

Richardson, D.M., Rejmánek, M., 2011. Trees and shrubs as invasive alien species – a global review. Divers. Distrib. 17, 788–809.

Richardson, D.M., van Wilgen, B.W., Higgins, S.I., Trinder-Smith, T.H., Cowling, R.M., McKell, D.H., 1996. Current and future threats to plant biodiversity on the Cape Peninsula, South Africa. Biodivers. Conserv. 5, 607–647.
Roper, B.B., Capurso, J.M., Paroz, Y., Young, M.K., 2018. Conservation of aquatic biodiversity in the context of multiple-use management on national forest system lands. Fisheries 43, 396–405.
Roura-Pascual, N., Krug, R.M., Richardson, D.M., Hui, C., 2010. Spatially-explicit sensitivity analysis for conservation management: exploring the influence of decisions in invasive alien plant management. Divers. Distrib. 16, 426–438.
Roura-Pascual, N., Richardson, D.M., Krug, R.M., Brown, A., Chapman, R.A., Forsyth, G. G., Le Maitre, D.C., Robertson, M.P., Stafford, L., Van Wilgen, B.W., Wannenburgh, A., Wessels, N., 2009. Ecology and management of alien plant invasions in South African fynbos: accommodating key complexities in objective decision making. Biol. Conserv. 142, 1595–1604.
Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26.
SANParks, 2016. Table Mountain National Park. Park Management Plan: 2015–2025, South Africa National Parks. Table Mountain National Park, Constantia.
Schwartz, M.W., Cook, C.N., Pressey, R.L., Pullin, A.S., Runge, M.C., Salafsky, N., Sutherland, W.J., Williamson, M.A., 2018. Decision support frameworks and tools for conservation. Conserv. Lett. 11, e12385.
Spear, D., McGeoch, M.A., Foxcroft, L.C., Bezuidenhout, H., 2011. Alien species in South Africa's national parks. Koedoe 53 (1), 4. Art. #1032.
Strydom, M., Veldtman, R., Ngwenya, M.Z., Esler, K.J., 2017. Invasive Australian Acacia seed banks: size and relationship with stem diameter in the presence of gall-forming biological control agents. PloS One 12, e0181763.
te Beest, M., Howison, O., Howison, R.A., et al., 2017. Successful control of the invasive shrub *Chromolaena odorata* in Hluhluwe-iMfolozi Park. In: JPGM, C., Archibald, S., Owen-Smith, N. (Eds.), Conserving Africa's Mega-Diversity in the Anthropocene: the Hluhluwe-iMfolozi Park Story. Cambridge University Press, Cambridge, pp. 358–382. https://doi.org/10.1017/9781139382793.020.
van Wilgen, B.W., Cowling, R.M., Marais, C., Esler, K.J., McConnachie, M., Sharp, D., 2012a. Challenges in invasive alien plant control in South Africa. South Afr. J. Sci. 108, 5–7.
van Wilgen, B.W., Dyer, C., Hoffmann, J.H., Ivey, P., Le Maitre, D.C., Moore, J.L., Richardson, D.M., Rouget, M., Wannenburgh, A., Wilson, J.R.U., 2011. National-scale strategic approaches for managing introduced plants: insights from Australian acacias in South Africa. Divers. Distrib. 17, 1060–1075.
van Wilgen, B.W., Fill, J.M., Baard, J., Cheney, C., Forsyth, A.T., Kraaij, T., 2016a. Historical costs and projected future scenarios for the management of invasive alien plants in protected areas in the Cape Floristic Region. Biol. Conserv. 200, 168–177.
van Wilgen, B.W., Fill, J.M., Govender, N., Foxcroft, L.C., 2017. An assessment of the evolution, costs and effectiveness of alien plant control operations in Kruger National Park, South Africa. NeoBiota 35, 35–59.
van Wilgen, B.W., Forsyth, G.G., Le Maitre, D.C., Wannenburgh, A., Kotzé, J.D.F., van den Berg, E., Henderson, L., 2012b. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. Biol. Conserv. 148, 28–38.
van Wilgen, B.W., Nel, J.L., Rouget, M., 2007. Invasive alien plants and South African rivers: a proposed approach to the prioritization of control operations. Freshw. Biol. 52, 711–723.
van Wilgen, B.W., Wannenburgh, A., 2016. Co-facilitating invasive species control, water conservation and poverty relief: achievements and challenges in South Africa's Working for Water programme. Curr. Opin. Environ. Sustain. 19, 7–17.
van Wilgen, B.W., Carruthers, J., Cowling, R.M., Esler, K.J., Forsyth, A.T., Gaertner, M., Hoffman, M.T., Kruger, F.J., Midgley, G.F., Palmer, G., Pence, G.Q.K., Raimondo, D. C., Richardson, D.M., van Wilgen, N.J., Wilson, J.R.U., 2016b. Ecological research and conservation management in the Cape Floristic Region between 1945 and 2015: history, current understanding and future challenges. Trans. Roy. Soc. S. Afr. 71, 207–303.
van Wilgen, B.W., Wilson, J.R., Wannenburgh, A., Foxcroft, L.C., 2020. The extent and effectiveness of alien plant control projects in South Africa. In: van Wilgen, B., Measey, J., Richardson, D., Wilson, J., Zengeya, T. (Eds.), Biological Invasions in South Africa, 14. Springer, Cham, Switzerland.
Vardien, W., Richardson, D.M., Foxcroft, L.C., Thompson, G.D., Wilson, J.R., Roux, J.J., 2012. Invasion dynamics of *Lantana camara* L. (sensu lato) in South Africa. South Afr. J. Bot. 81, 81–94.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer.
Working for Water Programme, 2017. Clearing History for Table Mountain National Park. Working for Water Information Systems. (Accessed 20 September 2018).